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Proposal and use of a void model for inclusion cracking for simulating inner fracture defects in drawing of ferrite–pearlite steels

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ABSTRACT

A void model for inclusion cracking is proposed and used for simulating inner fracture defects in the drawing of ferrite–pearlite steels. First, a void model for inclusion cracking is proposed based on the void model for inclusion-matrix separation previously proposed by the author. Next the simulation and experiment of the multipass drawing are performed using four types of ferrite–pearlite steels. The inner diameter of the die at which the material fractures, the material density distribution in the radial direction after drawing through the die preceding that at which the material fractures, and the material shape in the longitudinal section after drawing through the die at which the material fractures calculated from the simulation, are compared with those obtained experimentally. Finally, the validity of the proposed void model is confirmed by comparing the simulation and experimental results.

1. Introduction

Ductile fracture, which occurs when a material is subjected to a large plastic deformation, is a problem in metal-forming processes. Numerous ductile fracture criteria for various materials have been proposed. However, no ductile fracture criterion that is applicable to all metal-forming processes has been found (Clift et al., 1990; Wierzbicki et al., 2005).

Because ductile fracture occurs through nucleation, growth, and coalescence of voids (Dodd and Bai, 1987), it is a microscopic phenomenon. Because the ductile fracture criteria that are widely used for metal-forming processes, such as those introduced by Freudenthal (1950), Cockcroft and Latham (1968), Brozzo et al. (1972), and Oyane (1972), are derived from a macroscopic viewpoint, improving the accuracy of prediction of a microscopic ductile fracture phenomenon using a macroscopic ductile fracture criterion is inappropriate.

Recently, I have been attempting to predict ductile fracture in metal-forming processes from a microscopic viewpoint (Komori, 2013a, 2013b). My proposed void model is based on the Thomason (1968) model, which is also derived microscopically. The Thomason model assumes that the void is rectangular, whereas my proposed model assumes that the void is ellipsoidal. The Thomason model assumes that the direction of the major axis of the void coincides with the direction of the maximum principal stress, whereas my proposed model does not assume the coincidence of the two directions. Hence, my void model can be used in the simulation of metal-forming processes.

Nucleation of voids occurs through either inclusion cracking or inclusion-matrix separation (Goods and Brown, 1979). In my previous studies (Komori, 2013a, 2013b, 2014), in which circular voids are assumed to

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nucleate, a void that nucleates as a result of inclusion-matrix separation is considered. Hence, to improve the applicability of my void model, a void that nucleates as a result of inclusion cracking should be considered. However, the assumption that circular voids are assumed to nucleate is inappropriate. Hence, it is impossible to consider a void that nucleates as a result of inclusion cracking using my void model in its current form.

Extensive studies on the simulation of inclusion cracking have been performed to simulate the particle fracture or particle cracking in metal-matrix composites by the finite-element method (Bao, 1992; Finot et al., 1994; Brockenbrough and Zok, 1995; Steglich and Brocks, 1997; Ghosh and Moorthy, 1998). Because the shape of the crack is expressed by the finite-element mesh, the accuracy of the simulation result is high, whereas the computational time required for the simulation is large. Hence, it is inappropriate to apply the method of simulation in these studies to the simulation of ductile fracture behavior in metal-forming processes.

The ferrite–pearlite microstructure is a fundamental microstructure for carbon steels. Extensive studies have been conducted on the ductile fracture in ferrite–pearlite steels. These studies have demonstrated the nucleation of voids caused by the fracture of pearlite nodules and the growth and coalescence of voids caused by the propagation of cracks (Miller and Smith, 1970; Rosenfield et al., 1972; Inoue and Kinoshita, 1976a, 1976b). However, because these previous studies are experimental, an analytical study is required to clearly understand the effect of the ferrite–pearlite microstructure on ductile fracture.

In the present study, first, a void model for inclusion cracking is proposed, based on my void model for inclusion-matrix separation. Next, the simulation and experiment of the multipass drawing are performed using four kinds of ferrite–pearlite steels. Finally, the simulation results are compared with the experimental results to confirm the validity of the proposed void model.

2. Simulation method

The simulation method used in this study, which is the same as that in my previous study (Komori, 2013a, 2013b), is described briefly, whereas the new simulation method is described in detail.

2.1. Outline

A multiscale simulation is performed. The deformation of the material is simulated through a macroscopic simulation using the rigid-plastic finite-element method, whereas the fracture of the material is evaluated using the ellipsoidal void model through a microscopic simulation. The deformation gradient and void volume fraction calculated in the macroscopic simulation are used in the microscopic simulation, whereas determination of whether the material fractures, as evaluated in the microscopic simulation, is used in the macroscopic simulation.

The homogenization method (Terada and Kikuchi, 2003) is not used in this study. Hence, in each step, both the macroscopic and microscopic simulation are performed only once.

2.2. Outline of macroscopic simulation

The deformation of the material is simulated using the conventional rigid-plastic finite-element method (Kobayashi et al., 1989). Axisymmetry is assumed in the simulations of the multipass drawing and the uniaxial tensile test. The yield function proposed by Gurson (1977) is adopted:

$$\Phi = \frac{3}{2}\cdot\frac{\sigma'_{ij}\sigma'_{ij}}{\sigma_{\mathrm{M}}^2} + 2f\cosh\left(\frac{\sigma_{kk}}{2\sigma_{\mathrm{M}}}\right) - 1 - f^2 = 0, \tag{1}$$

where σ_{M} is the tensile yield stress of the matrix and f is the void volume fraction of the material. Because the yield function Φ is not a function of the second power of stress, it is not easy to perform a rigid-plastic simulation using Eq. (1). Hence, $\cosh x$ is approximated to be $1 + x^2/2$ (Tomita, 1990). Therefore, the approximated yield function Φ' used in this study is

$$\Phi' = \frac{3}{2}\cdot\frac{\sigma'_{ij}\sigma'_{ij}}{\sigma_{\mathrm{M}}^2} + \frac{f}{4}\cdot\left(\frac{\sigma_{kk}^2}{\sigma_{\mathrm{M}}^2}\right) - (1-f)^2 = 0. \tag{2}$$

The following evolution equation (Komori, 2006, 2013b), which denotes the change in the void volume fraction, is assumed:

$$\dot{f} = (1-f)\dot{\varepsilon}_{kk} + A\cdot R\left(\frac{\sigma_{kk}}{3\bar{\sigma}} - B\right)\dot{\bar{\varepsilon}}, \tag{3}$$

where $\bar{\sigma}$ is the equivalent stress, $\dot{\bar{\varepsilon}}$ is the equivalent strain rate, and A and B are material constants. $R(x)$ in Eq. (3) denotes the ramp function. In other words, when x is positive, $R(x)$ is x, whereas when x is negative, $R(x)$ is zero. The first and second terms on the right-hand side of Eq. (3) denote void growth and void nucleation, respectively.

The material fracture is simulated, as described in my previous studies (Komori, 1999, 2003), by the node separation method (Brokken et al., 1998, 2000; Komori, 2001). At each step, the tool displacement is controlled such that only one element fractures; i.e., one node is separated into two nodes such that one side of the fractured element can be separated, or two nodes are separated into four nodes such that two sides of the fractured element can be separated. No remeshing is performed because the deformation of the material is not large.

2.3. Outline of microscopic simulation

Following is an outline of the microscopic simulation performed in each step, from the calculation of the void volume fraction and deformation gradient to the determination of whether the material fractures:

(1) The void volume fraction f and deformation gradient $\partial\mathbf{x}/\partial\mathbf{X}$ are calculated by the macroscopic rigid-plastic finite-element simulation.
(2) The void configuration and void shape are calculated.